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SUBJECT: Studies of ORNL Stack Monitoring - I. Improvement of the 3018 Stack Sampling System

TO:

FROM: J. W. Youngblood and B. R. Fish

INTRODUCTION

Radioactive contaminants dispersed through the ORNL stack system are controlled by the Operations Division and are monitored by the Operations and the Health Physics Divisions. Although the regulatory and the monitoring functions may require that essentially different types of samples be collected for the different purposes, one requirement common to both responsibilities is that the samples must accurately reflect the concentrations of radioactive materials in the effluent gases. There is reason to believe that this basic criterion is not being met by the present 3018 stack sampling system. A discussion of some of the more obvious sources of deviation from representative sampling constitutes the substance of this review. In this report no consideration is given either to aerosol collection media or to the associated detection system. These features are certainly important to the regulatory-monitoring effort and will be discussed in future reports; however, the purpose of this study is to evaluate the integrity of the sample delivered at the end of the sampling line and to propose an alternate system if such seems warranted. On a theoretical basis, it does appear that the present system can be improved, and a new sample delivery line is suggested as a means of minimizing the errors imposed by the present sampling system.

SAMPLING ERRORS

Collecting representative samples of particles and vapors suspended in a moving gas stream requires critical attention to deposition in sample delivery lines. If some degree of line loss is unavoidable, it is important to know the magnitude of the sampling error and to minimize variations related to parameters such as gas temperature and particle size.

ISOKINETIC SAMPLING

Inertial effects may be introduced unless the particle-laden gas enters the sampling nozzle at a velocity identical to that prevailing in the main gas stream, i.e., isokinetic sampling is required. Departure from this condition produces errors when the particles are larger than the aerodynamic equivalent of a 5-micron-diameter sphere of unit* density.(1) The effect is the result of the failure of large particles to follow abrupt changes in the direction of the gas stream. When the main stream velocity exceeds that entering the sampling orifice, much of the gas approaching the nozzle is diverted around it, but the larger particles traverse the gas stream lines and enter the opening. As a result, the measured concentration of particles exceeds the true value. On the other hand, when the sampling velocity exceeds that of the main gas stream, a portion of the approaching gas is diverted into the nozzle while the larger particles continue past, and, as a result, the concentration in the sample line is less than that in the main stream.

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*The aerodynamic properties of spherical particles are directly related to their size and density. It is standard practice to normalize to unit density when treating aspects of particle transport and deposition which are essentially aerodynamic in nature. (See discussion on page 13.)

The errors resulting from anisokinetic sampling of gas streams with low Reynolds numbers can be estimated with the following equation by Watson:[2]

$$\frac{C}{C_o} = \frac{V_o}{V} \left\{ 1 + f(p) \left[\left(\frac{V}{V_o} \right)^{1/2} - 1 \right]^2 \right\} \qquad (1)$$

where

C_o = true particle concentration

C = measured particle concentration

V_o = main gas stream velocity

V = gas velocity into nozzle orifice

and

p = $d^2 \rho_p V_o / 18 \mu D$

ρ_p = specific gravity of particle

d = diameter of particle

μ = gas viscosity

D = orifice diameter

Values for the parameter $f(p)$ were determined experimentally by Watson and may be found in the reference to his work.

There is no equivalent theoretical basis for estimating the effects of anisokinetic conditions at Reynolds numbers representative of turbulent flow. Under these conditions, the effect of anisokinetic sampling is a function of the size, velocity, and distribution of the individual eddies as well as being related to particle size. Although there is no available means of estimating the magnitude of the anisokinetic effect under turbulent flow, it is evident that additional turbulence in the region about the nozzle should be avoided, and in order to accomplish this, the sampling velocity should equal the average stream velocity at the sampling point. Experimental data reported in the literature[2,3,12] indicate that considerable error may be produced by nonisokinetic collection of particulate materials (> 10 microns) from high velocity gas streams.

Location of the Sampling Point

Variations in particle concentration as well as size distribution may result from turbulence and any change in the velocity or direction of the gas stream; hence, the location of the sampling nozzle is important for sampling at all Reynolds numbers. In some instances, a single sampling point is not sufficient and samples must be collected at several locations. To reduce the effects of disturbances in the gas stream and to permit the establishment of a stable flow regime, it is generally recommended that sampling locations be at least 10 duct diameters downstream from the nearest obstruction.[4]

Line Loss

Some of the vapors and the particulate material suspended in a gas stream will deposit onto the conduit walls. The fraction deposited varies with the diffusion coefficient of the entrained vapors and gases, the size and density of the particles, the gas flow rate, and the dimensions and configuration of the conduit. Deposition of vapors and gases on conduit walls is controlled by their rate of diffusion across the boundary layer at the wall surface. Losses may become appreciable for volatile and chemically active fission gases, such as iodine.

Estimates of the magnitude of the loss of gases from laminar streams can be obtained using the equation of Gormley and Kennedy:[5]

$$f = 1 - 0.8191\, e^{-7.314\, h} - 0.0975\, e^{-44.6\, h} - 0.0325\, e^{-114\, h} \qquad (2)$$

in which

f = fraction deposited in length x of conduit

$h = \frac{\pi\ x\ C_D}{2\ Q}$

where

C_D = diffusion coefficient

Q = volumetric flow rate in the conduit.

The principal mechanisms for particle deposition are gravitational settling, thermal forces, Brownian motion, electrical forces, and turbulent eddies.[6] Additional losses result when sharp bends, abrupt transitions, and condensation occur in the delivery lines. Studies of the deposition mechanisms indicate that, except for very small particles suspended in a large thermal gradient or transported at low flow rates, the controlling deposition mechanisms are gravitational settling and turbulent diffusion.[7]

Gravity Settling

Gravity settling occurs when the density of a particle exceeds that of its supporting fluid. For horizontally aligned conduits and laminar flow the settling velocity and the radial velocity component are equal. To minimize settling losses of the heavier particles, a flow rate should be employed just short of that producing turbulence. If a higher rate than this is necessary to reduce settling losses, the induced turbulence may result in deposition offsetting any decrease in the loss from settling. Since the radial component of the settling velocity is zero for spherical particles in a vertically aligned duct, deposition losses from gravitational settling do not occur.

A discussion of turbulent diffusion is given in the following section describing the present sampling system for the 3018 stack duct.

PRESENT 3018 STACK SAMPLING SYSTEM

The purpose of this report is to describe the system presently used to sample the 3018 stack effluent, to estimate the magnitude of the deposition losses in the system in terms of the controlling deposition mechanism, and to compare these with losses in a proposed system designed to minimize deposition.

ORNL Graphite Reactor cooling air and the Low Intensity Test Reactor off-gas are dispersed through the 200-foot 3018 stack. The total volume, principally cooling air, is approximately 120,000 CFM. Each gas stream passes through a filtering system (Fig. 1) before reaching the stack.

Cooling air from the Graphite Reactor enters at the top of the filter house, passes downward through a set of fiberglass roughing filters, and then passes horizontally through a polishing filter into the exit duct. Each roughing filter consists of one layer of A.A.F. Filterdown F.G. No. 25 and one layer of F.G. No. 50. The polishing filters are of AEC No. 1 or CWS No. 6 pleated paper and have a rated retention efficiency exceeding 99 per cent for 0.3 micron diameter or larger particles.[8]

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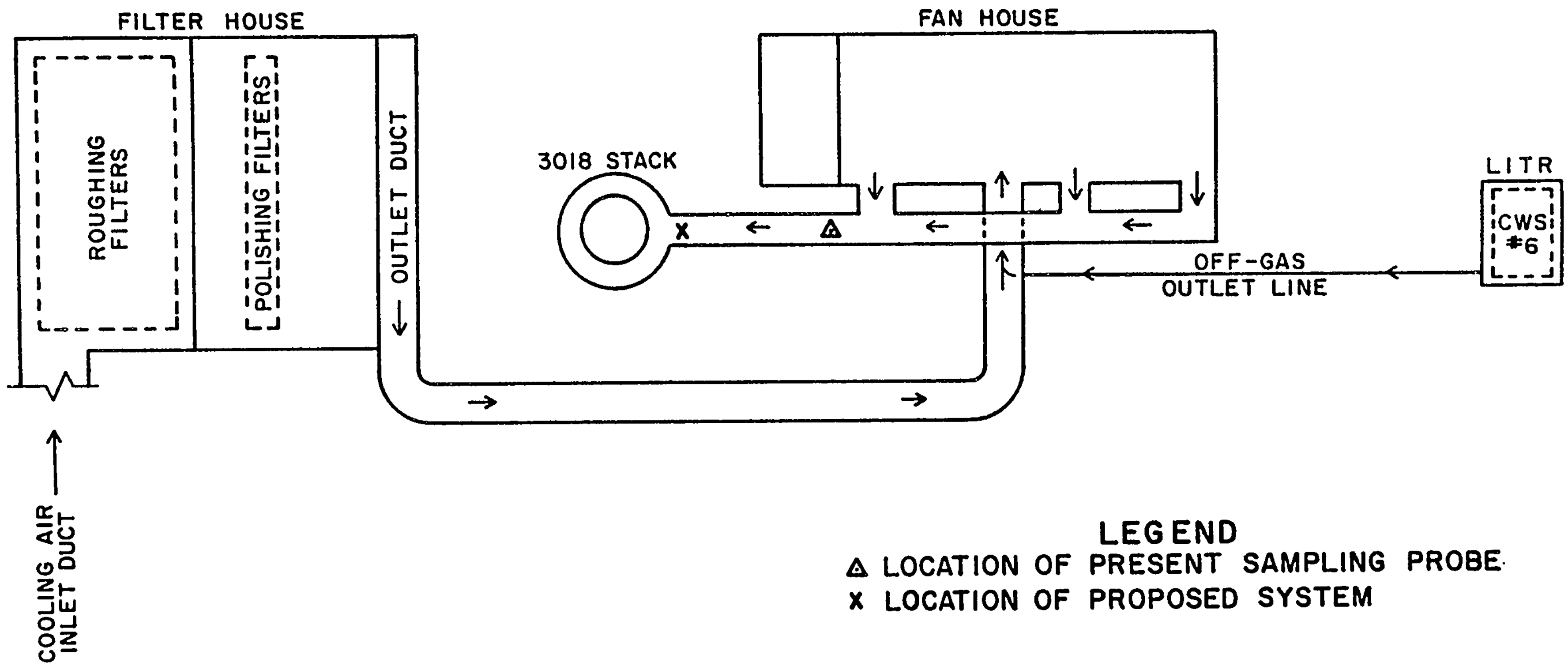

FIG. I FILTER AND FAN SYSTEM FOR 3018 STACK

Neutron activation and the escape of fission products from fuel elements result in radionuclides being present in the moderating and cooling water of the LITR. This water is circulated through a cooling system and is held up in a header tank which maintains the water level above the fuel elements in case of a malfunction in the recirculation system. Gases and vapors evolved from the cooling water collect in the gas space in the header tank and are vented through CWS No. 6 filters along with the off-gases from in-pile experiments. After filtering, these gases and vapors are passed over activated charcoal adsorbers. Following this treatment at the LITR reactor building, the gases are vented through a 500-CFM off-gas system and combined with the Graphite Reactor cooling air just before entering the fan house. The effluent then passes through an elevated duct at an average flow velocity of 100 ft/sec and is discharged into the 3018 stack.

The reinforced concrete duct is rectangular in cross-section with inside dimensions 4 x 5 ft. Effluent from the fan house enters the duct through three openings, the last being 30 feet upstream from the stack.

Approximately 300 CFM, out of the total 120,000 CFM, is circulated through the present sampling system diagrammed in Fig. 2. A 4-inch conduit enters the duct just below its midheight and 8 feet downstream from the last fan-house opening. Inside the duct the sample pipe is bent sharply 90° to point upstream. Outside the duct the conduit makes two additional 90° bends and enters the west room of the fan house. It extends horizontally for 15 feet, makes a 180° bend, exits from the room, and connects to the low pressure side of the fans. A pressure drop of 57 inches H_2O exists between this point and the duct and is

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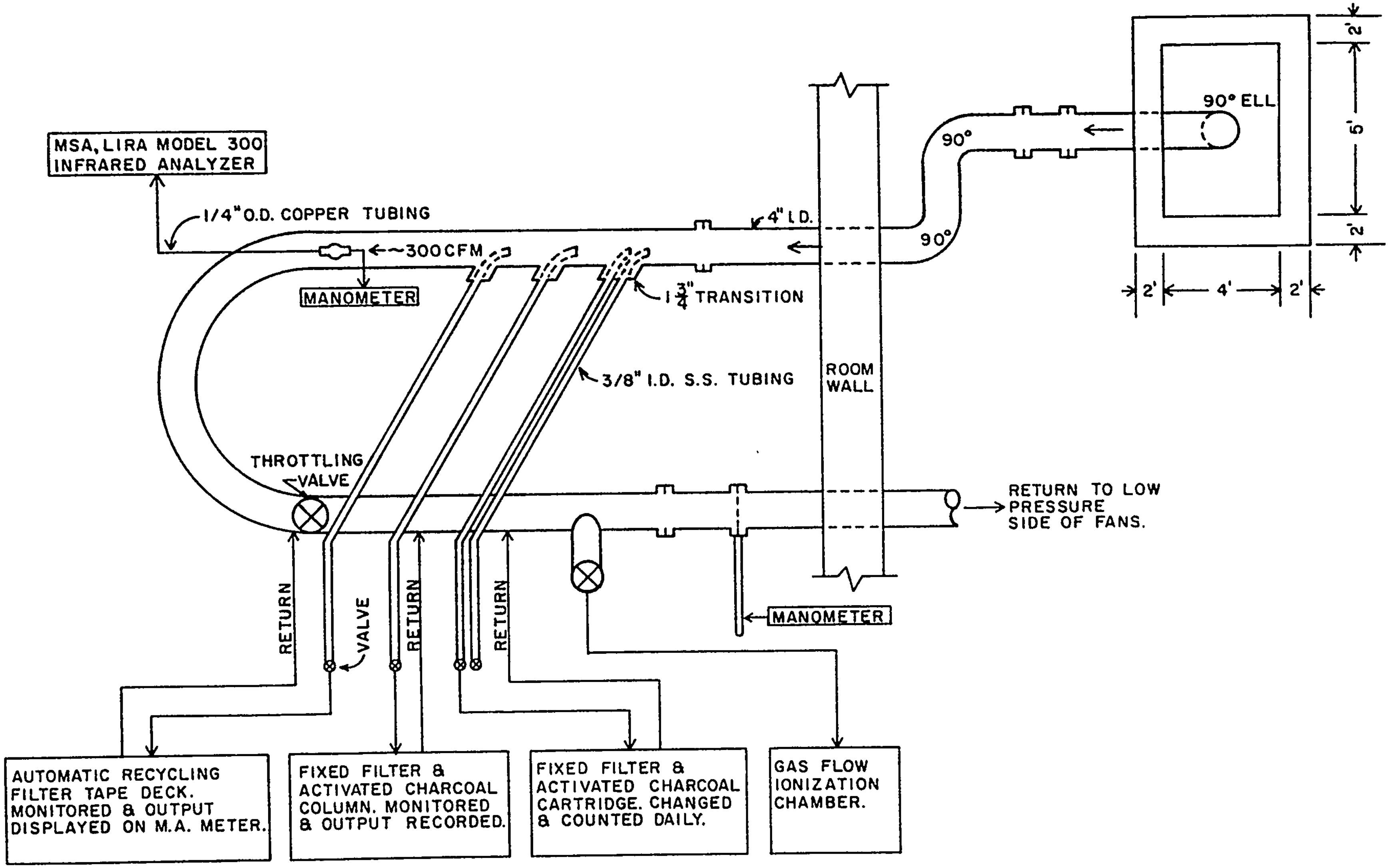

FIG.2 PRESENT SAMPLING SYSTEM FOR 3018 STACK EFFLUENT

used to obtain the 300 CFM flow rate. Portions of this volume are drawn through lengths of 1/2-inch tubing connected to the underside of the inlet half of the conduit loop and are sampled and monitored by the various means noted in Fig. 2.

Sample validity is affected by anisokinetic sampling and by deposition losses occurring in the delivery line. For the present system, the ratio of sampling velocity to main stream velocity is approximately 2:1. Information concerning the size of effluent particles is lacking, and because of the close proximity of the sampling nozzle to the disturbance created by the fan opening, a quantitative estimate cannot be made of the sampling errors.

Loss of I^{131} vapor by deposition in the system is estimated to be 30 per cent, based upon equation (2). However, that equation is restricted to laminar flow conditions, while the Reynolds number associated with the present sampling system is 98,500, corresponding to highly turbulent flow. Although an accurate assessment cannot be made, the actual loss will be in excess of 30 per cent since the boundary layer thickness controlling the diffusion rate to the conduit walls is inversely proportional to the Reynolds number.[9]

As a result of the flow conditions in the sample delivery line, turbulent diffusion is the controlling mechanism for particle deposition. Postma and Schwendiman[10] have found that the fraction of inlet particles remaining in suspension after passage through a length of conduit is expressible as:

$$\frac{C}{C_o} = \exp\left\{-\frac{4L}{D}\left(\frac{K}{V}\right)\right\} \tag{3}$$

where

C_o = inlet particle concentration

C = particle concentration at L

L = conduit length

D = conduit diameter

V = average gas velocity

K = particle deposition velocity

Experimental data were correlated by plotting the dimensionless parameters

$$\left(\frac{K}{V}\right) \quad \text{against} \quad \left(\frac{D}{a}\right)^n \left(\frac{\rho_p d^2 f V^2 \rho_g}{\mu^2 + \mu b \rho_p d^2}\right)$$

in which

D = conduit diameter

d = particle diameter

ρ_p = particle density

ρ_g = gas density

μ = gas viscosity

f = Fanning friction factor

a = constant = 1 cm

n = constant = 0.84

b = constant = 13.5 sec^{-1}

On the basis of these data, particle deposition velocities may be estimated for several combinations of particle, conduit, and sampling parameters. Calculations have been made to determine the fraction

$(1 - \frac{C}{C_o})$ of unit density spheres which will deposit in the 4-inch and 1/2-inch delivery lines of the present sampling system. The results are shown in Fig. 3, where the fraction deposited is plotted as a function of particle diameter. Unit density particles were assumed due to the lack of data in support of any alternate assumption. The deposition loss of particles having different densities can be obtained from the curve using the relationship $\rho_1 d_1^2 = \rho_i d_i^2$; this says that particles of density ρ_i and diameter d_i have a deposition loss equal to that of unit density particles with diameter d_1, for which values from 1 to 10 microns can be read from Fig. 3. It is apparent that retention losses for particles smaller in size than the equivalent of 1-micron-diameter spheres of unit density are not appreciable, whereas over 98 per cent of the 10-micron particles are lost to the conduit walls. Particles smaller than 10 microns equivalent diameter are of respirable size and those below 5 microns are capable of penetrating to the alveolar spaces of the lung.(11) It is evident from Fig. 3 that a large fraction of the particles in this important size range are lost to the conduit walls. Furthermore, the bulk of the particulate radioactivity released to the environment may consist of a few large particles flaking off the fan blades or duct walls and they, likewise, would be retained in the sample delivery line.

Sampling losses are expected to be considerable in the present system and some cognizance must be given to line loss in order to insure meaningful results. Obviously, a knowledge of the particle sizes present in the sampled stream is required before valid estimates of line losses can be made. However, since the radioactivity associated

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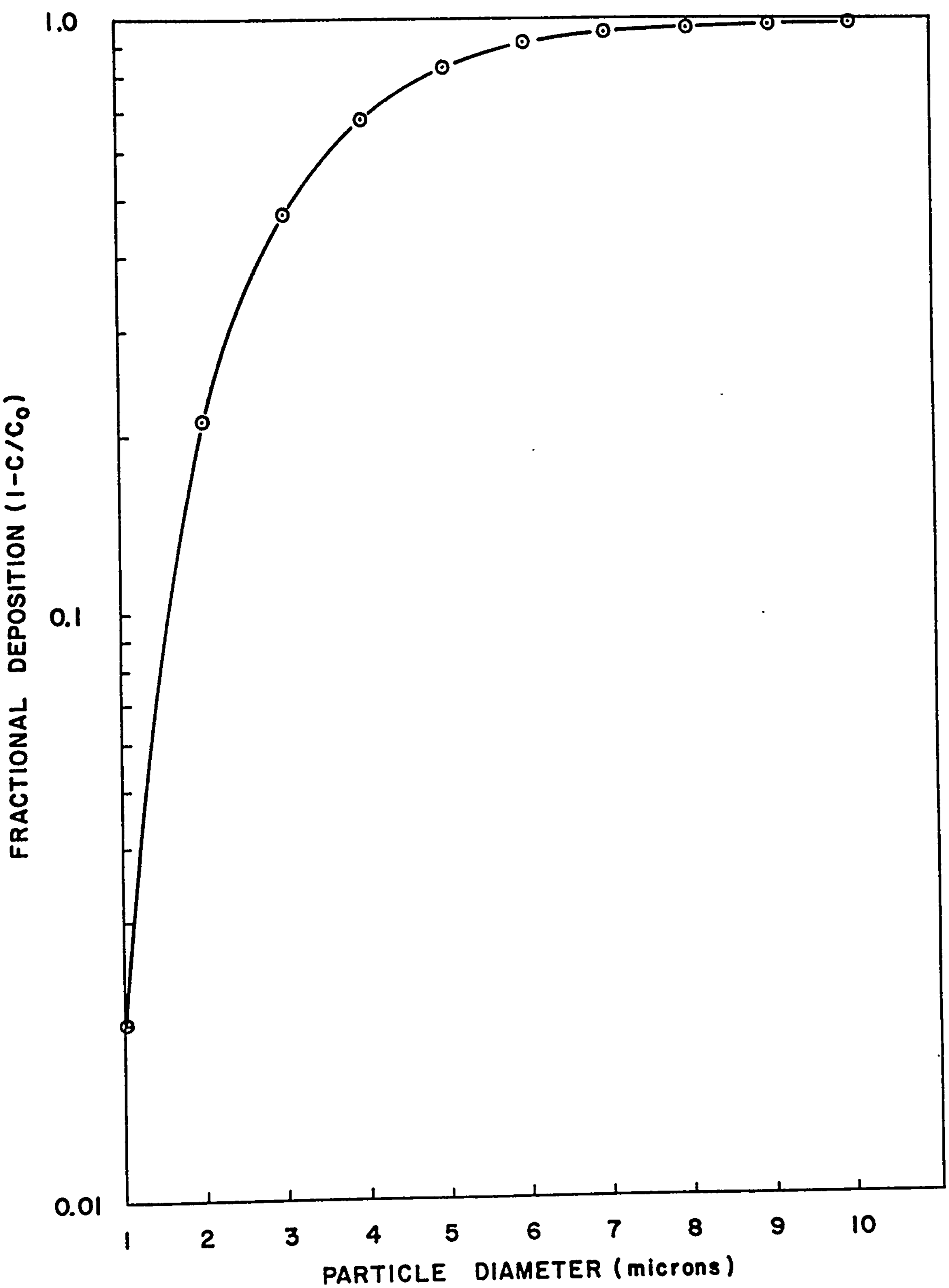

FIG. 3 FRACTION OF THE PARTICLES DEPOSITED BY TURBULENT DIFFUSION IN PRESENT SAMPLING SYSTEM AS A FUNCTION OF PARTICLE SIZE

with a particle is not necessarily a function of its physical size, factors based only upon physical dimensions may be meaningless in attempting to correct for radioactivity losses in a conduit. The best alternative is to minimize line losses by every practicable design means.

MINIMIZING LINE LOSS

Deposition losses may be eliminated by placing the collecting medium in the gas stream being sampled, or losses may be reduced by employing a probe and delivery line system designed to minimize the effects of the deposition mechanisms. Both methods have advantages - the former in collecting samples for subsequent laboratory analyses and the latter in the continuous instrumental surveillance of samples delivered to a point outside the relatively high and variable radiation background associated with the effluent duct.

To minimize losses,certain conditions should be avoided where possible - sharp bends, abrupt transitions, adverse thermal gradients, horizontal sections, long lengths, and turbulent flow. Based upon these restrictions, a system has been designed for use in the 3018 stack duct, Fig. 4.

In the absence of data to support any alternate conclusion, the center of the duct was assumed to be the best location for representative sampling. A 2.5-foot radius bend in the conduit will allow the sampling orifice to be placed at the center when the probe is mounted through the bottom wall. In such a position, the length of horizontal conduit is minimized; hence gravity settling losses should be reduced. To reduce the effects of the disturbance created by the last fan opening and to

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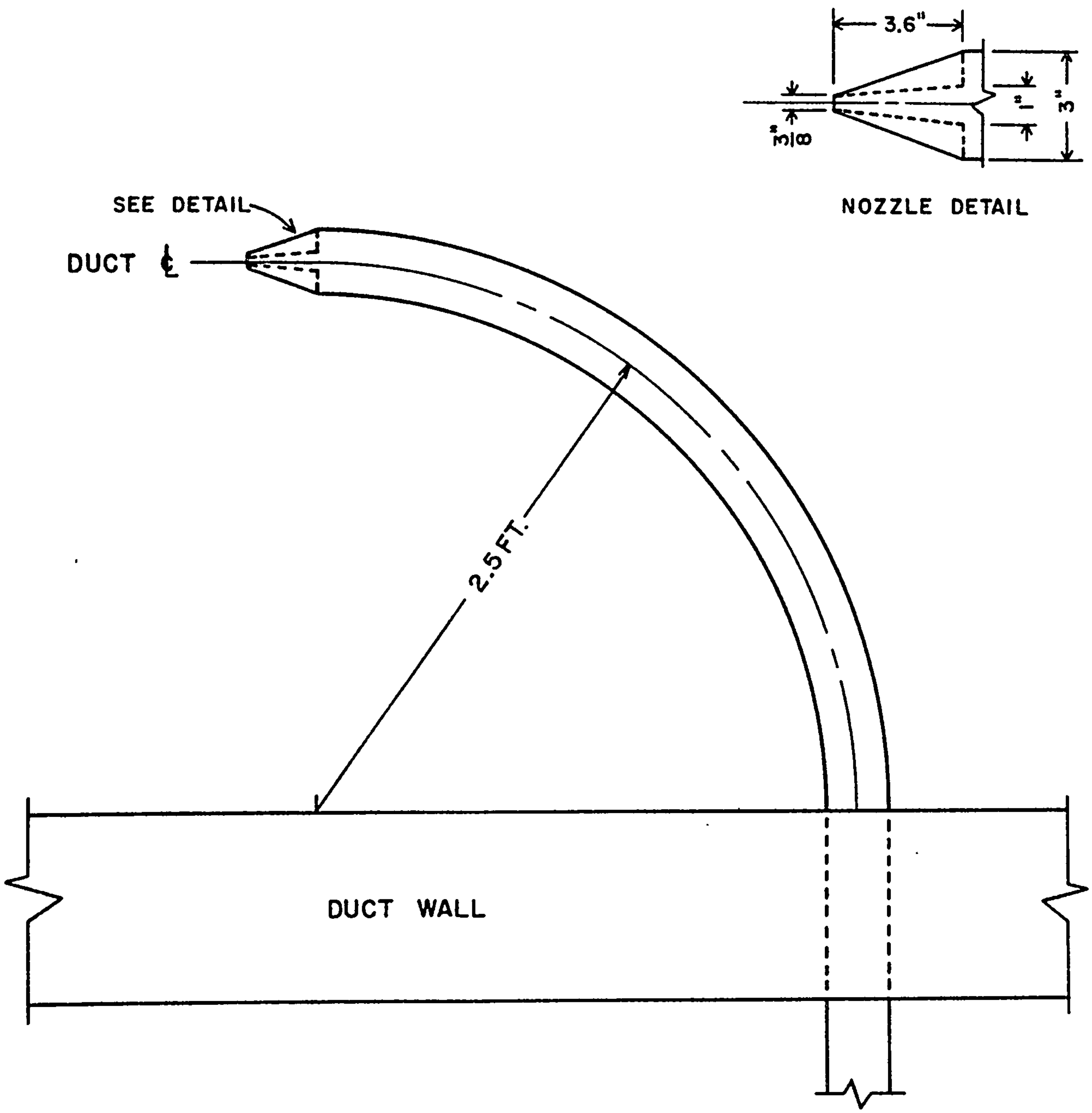

FIG. 4 PROPOSED SAMPLING PROBE FOR MINIMIZING DEPOSITION LOSSES

allow for the establishment of a more stable flow regime, the probe should be located near the duct entrance to the stack.

Heating the probe is recommended to eliminate the variable thermal gradient existing between the effluent at 75°C and the changing temperature of the surrounding environment. This prevents thermal deposition losses of small particles and also minimizes the condensation of water vapor and the more volatile fission products such as iodine.

Isokinetic sampling can be achieved through the use of a 3/8"-diameter sampling orifice and a sampling rate of 4.6 CFM, resulting in laminar flow in the conduit. Since orifices smaller than this produce sampling errors even under isokinetic conditions,[12] the proposed orifice and sampling rate are the minimum required to match the 100-ft/sec flow rate in the duct.

Expansion of the gas stream in passing from the 3/8" orifice to the 3" conduit will result in the production of eddy currents in the immediate vicinity of the orifice. These arise primarily from the shock, or Borda, loss produced by the impact of the high velocity gas from the orifice colliding with the slower moving gas in the large conduit. Using a gradually tapering enlargement diminishes the eddies created by the reduction in velocity. However, this necessitates a long taper in which friction becomes a major producer of eddies. The sampling nozzle in Fig. 4 is based on a compromise enlargement design by Gibson[13] for optimal reduction of turbulence producing effects.

For the proposed system, the <u>maximum</u> I^{131} deposition loss, based on equation (2), is expected to be 20 per cent compared to a <u>minimum</u> of 30 per cent for the present system. However, these values are not exactly comparable since that for the existing system does not include additional losses resulting from turbulent flow, adverse thermal gradients, and sharp bends present in the system, while the value for the proposed system does not take into account the decrease in deposition produced by heating the conduit walls.

Centrifugal action of the gas stream in flowing around the bend in the probe is the controlling mechanism for particle deposition. Forstat and Boyd[14] developed the following expression which described the trajectories of particles in a gas stream:

$$\ln \left\{ \frac{E - \left[E^2 - d(R-0.25d)\right]^{1/2}}{E + \left[E^2 - d(R-0.25d)\right]^{1/2}} \cdot \frac{(E + \delta)}{(E - \delta)} \right\} = -\rho_p \, QEd^2/9\mu R^4 \qquad (4)$$

where

d	=	particle diameter, cm
ρ_p	=	particle density, g/cm^3
R	=	conduit radius, cm
δ	=	vertical displacement of incoming particle from center of conduit, cm
γ	=	horizontal displacement of incoming particle from center of conduit, cm
E	=	$(R^2 - \gamma^2)^{1/2}$, cm
Q	=	gas flow rate, cm^3/sec
μ	=	gas viscosity, g/cm - sec

Equation (4) represents the condition that a particle with diameter d, and density ρ_p is just deposited after passing around the conduit bend. For different values of d and ρ_p contour impingement curves can be obtained by plotting values of γ versus δ. Impingement curves for the suggested system are shown in Fig. 5 for unit density spheres. Particles of a specific size passing through the cross-sectional area of the conduit lying above the contour for that size will be deposited along the outside wall. For uniformly dispersed particles, the number of particles of a specific size entering a conduit through the cross-sectional area above a given contour is proportional to the cross-sectional area above the contour. By this approach, an estimate of the impingement loss as a function of particle size was made for the 3" conduit. This resulted in the S-shaped curve shown in Fig. 6, which indicates that deposition losses will be slight for unit density equivalent particles smaller than 300 microns in diameter. Despite the fact that the Graphite Reactor cooling air and the LITR off-gas are filtered prior to discharge, large particles may appear in the effluent. These normally result from the coalescing and the flaking off, as large aggregates, of the small particles deposited on surfaces in the fan and duct systems. Thus, the sampling system should insure small deposition losses for large as well as for small particles. This need was emphasized by the Ru^{106} fallout incident of November, 1959, in which the release is reported[15,16] to have been caused by ruthenium being dislodged from a fan (3039 stack) during maintenance work. The release was discovered when contamination was found in office areas and on the shoes of several laboratory employees. A subsequent analysis of the stack monitor filter showed only a trace quantity of the isotope despite the fact that enough was deposited on a short section of the 1" delivery line to give a direct reading of 10 mrad/hr. This factor

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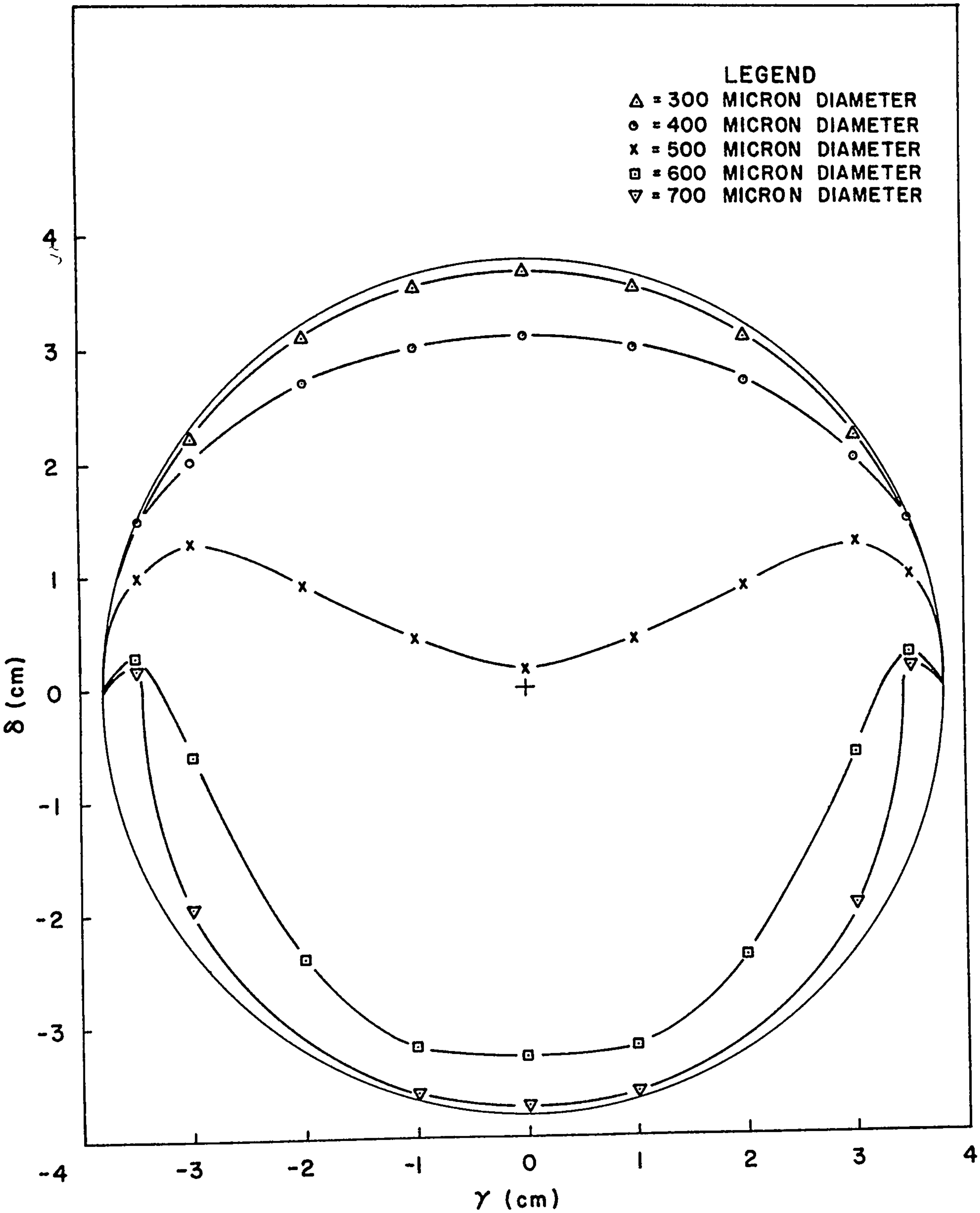

FIG. 5 CONTOUR CURVES FOR PARTICLE IMPINGEMENT IN PROPOSED SAMPLING PROBE

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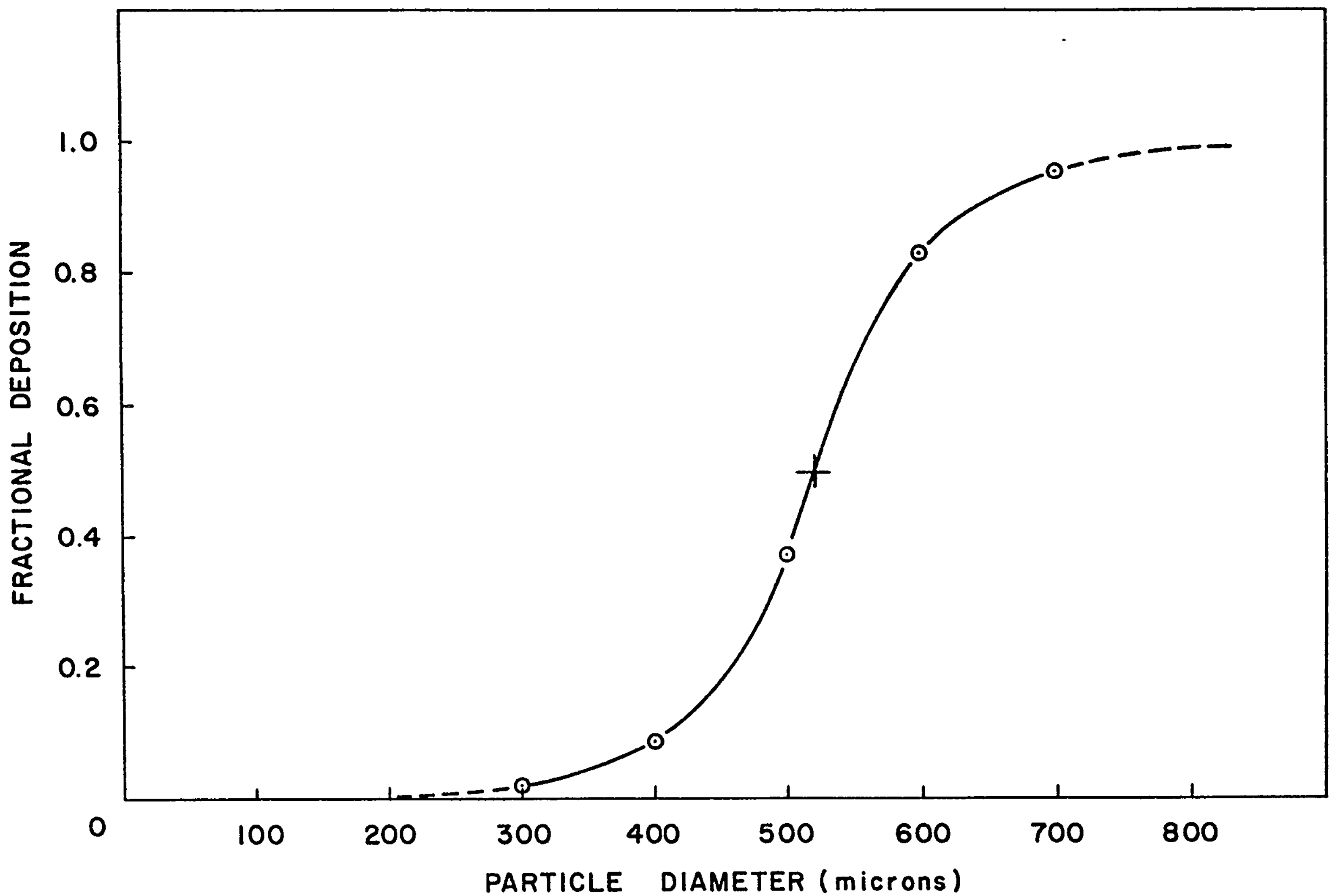

FIG. 6 FRACTION OF THE PARTICLES IMPINGED IN THE PROPOSED SAMPLING PROBE AS A FUNCTION OF PARTICLE SIZE

of line deposition along with the observed close-in fallout indicated that the dislodged particles were of large size and were essentially 100 per cent deposited on the wall of the 1" sample delivery line.

A comparison between the fractional deposition curve for the existing 3018 sampling system (Fig. 3) and that for the suggested system (Fig. 6) illustrates the magnitude of the prospective improvement in sample validity through the use of the new system. A significant reduction in deposition losses may be expected as a result of avoiding adverse thermal gradients, turbulent flow, long horizontal sections, sharp bends, and abrupt transitions in the conduit. Because of the serious consequences of not collecting samples adequate to detect the flaking of material from duct or fan parts, or to indicate a sudden failure of the filters, the sampling system should not impose a large fractional line loss for large particles.

RECOMMENDATIONS

On the basis of these observations, it is recommended that three 7"-diameter holes be made through the underside of the 3018 duct immediately upstream from the entrance to the stack. These holes would be used to introduce sampling probes into the duct to determine velocity profiles, particle size distribution, and particle concentration distribution within the 3018 stack duct. This further study would permit determining the final size, position, and number of probes needed to insure collecting a valid sample of the 3018 stack effluent for continuous monitoring and for laboratory analysis.

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